Global Glacier Changes: The state of knowledge after IPCC AR5

Frank Paul

Department of Geography, University of Zurich

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4. Randolph Glacier Inventory
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The new WGI IPCC report (AR5)

Headline Statements from the Summary for Policymakers

Observed Changes in the Climate System

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.

Cryosphere in IPCC AR5: Authors & Results

Observations: Cryosphere

Glaciers

Since AR4, almost all glaciers worldwide have continued to shrink as revealed by the tim series of measured changes in glacier length, area, volume and mass (very high confidence). Measurements of glacier change have increased substantially in number since AR4. Most of the new data sets, along with a globally complete glacier inventory, have been derived from satellite remote sensing. (4.3.1, 4.3.3, Figures 4.9, 4.10, 4.11)

Between 2003 and 2009, most of the ice lost was from glaciers in Alaska, the Canadian Arctic, the periphery of the Greenland ice sheet, the Southern Andes and the Asian Mountains (very high confidence). Together these regions account for more than 80% of the total ice loss. (4.3.3, Figure 4.11, Table 4.4)

Total mass loss from all glaciers in the world, excluding those on the periphery of the ice sheets, was very likely $226 \pm 135$ Gt yr$^{-1}$ (sea level equivalent, $0.62 \pm 0.37$ mm yr$^{-1}$) in the period 1971–2009, 275 $\pm 135$ Gt yr$^{-1}$ (0.76 $\pm 0.37$ mm yr$^{-1}$) in the period 1993–2009, and 301 $\pm 135$ Gt yr$^{-1}$ ($0.83 \pm 0.37$ mm yr$^{-1}$) between 2005 and 2009. (4.3.3, Figure 4.12, Table 4.5)

Current glacier extents are out of balance with current climatic conditions, indicating that glaciers will continue to shrink in the future even without further temperature increase (high confidence). (4.3.3)
IPCC AR5: The global cryosphere

Each glacier is individual
Different methods are used to determine changes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Method</th>
<th>Technique</th>
<th>Typical accuracy</th>
<th>Number of Glaciers</th>
<th>Repeat Interval</th>
<th>Earliest Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length change</td>
<td>Various</td>
<td>Reconstruction</td>
<td>10 m</td>
<td>Dozens</td>
<td>Decadal – centuries</td>
<td>Holocene</td>
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<tr>
<td>Field</td>
<td>In situ measurement</td>
<td></td>
<td>1 m</td>
<td>Hundreds</td>
<td>Annual</td>
<td>19th century</td>
</tr>
<tr>
<td>Remote Sensing</td>
<td>Photogrammetric survey</td>
<td>Two image pixels (depending on resolution)</td>
<td>Hundreds</td>
<td>Annual</td>
<td>19th century</td>
<td></td>
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<tr>
<td>Area change</td>
<td>Maps</td>
<td>Cartographic</td>
<td>5% of the area</td>
<td>Hundreds</td>
<td>Decadal</td>
<td>19th century</td>
</tr>
<tr>
<td>Remote sensing</td>
<td>Image processing</td>
<td></td>
<td>5% of the area</td>
<td>Thousands</td>
<td>Sub-decadal</td>
<td>20th century</td>
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<tr>
<td>Volume change</td>
<td>Remote sensing</td>
<td>Laser and radar profiling</td>
<td>0.1 m</td>
<td>Hundreds</td>
<td>Annual</td>
<td>21st century</td>
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<tr>
<td></td>
<td>Remote sensing</td>
<td>DEM differencing</td>
<td>0.5 m</td>
<td>Thousands</td>
<td>Decadal</td>
<td>20th century</td>
</tr>
<tr>
<td>Mass change</td>
<td>Field</td>
<td>Direct mass balance measurement</td>
<td>0.2 m</td>
<td>&gt;450 annually</td>
<td>Seasonal</td>
<td>20th century</td>
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<tr>
<td></td>
<td>Remote sensing</td>
<td>Gravimetry (GRACE)</td>
<td></td>
<td>Global</td>
<td>Seasonal</td>
<td>21st century</td>
</tr>
</tbody>
</table>

Key research questions for AR5
- Compilation of a globally complete glacier inventory
  - glacier area and volume, spatial extrapolation, future development
- Overall contribution to global SLR (in-situ, dDEMs, altimetry)?
- Separating the local glaciers on Greenland from the ice sheet
- What is going on in High-Mountain Asia?

Fluctuations on a millennia to decadal time scale

Example Pasterze:
ΔL: -1250 m / 125 a = -10 m/a, 
ΔT: +1.25 °C / 125 a = +0.1 °C/10 a
Global length changes

- Largely globally homogenous retreat at the millennia time scale (km range)
- Intermittent phases of re-advance in several regions at decadal time scale
- Some glaciers exhibit special conditions (calving, surging, debris)
- Quantitative values not to be averaged only possible for general trends
- Signal comes from mountain glaciers

How do glacier react to climate change?

Before climate change

IPCC (2013)
How do glacier react to climate change?

After climate change but before glacier readjustment

IPCC (2013)

How do glacier react to climate change?

After readjustment to climate change

IPCC (2013)
How does this look like in reality?

1985: Good conditions

2003: Poor conditions

Creating a glacier inventory

GIS based analysis

Inventory Alps
The RGI is a merged product: Example HMA

The Randolph Glacier Inventory (RGI)
The Randolph Glacier Inventory (RGI)

- 170,000 glaciers worldwide covering 730,000 km²
- Volume of about 170,000 km³ or 41 cm SLE
- Numbers will change through RGI updates

<table>
<thead>
<tr>
<th>Region</th>
<th>Region Name</th>
<th>Number of Glaciers</th>
<th>Area (km²)</th>
<th>Percent of total area</th>
<th>Tidewater fraction (%)</th>
<th>Mass (minimum) (Gt)</th>
<th>Mass (maximum) (Gt)</th>
<th>Mean SLE (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Alaska</td>
<td>23,112</td>
<td>89,267</td>
<td>12.3</td>
<td>13.7</td>
<td>16,168</td>
<td>28,021</td>
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<td>2</td>
<td>Western Canada and USA</td>
<td>15,073</td>
<td>14,503.5</td>
<td>2.0</td>
<td>0</td>
<td>906</td>
<td>1146</td>
<td>2.8</td>
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<td>Arctic Canada North</td>
<td>3318</td>
<td>103,990.2</td>
<td>14.3</td>
<td>46.5</td>
<td>22,366</td>
<td>37,555</td>
<td>84.2</td>
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<td>5510</td>
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<td>Greenland</td>
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<td>34.9</td>
<td>10,055</td>
<td>17,146</td>
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<td>10,988.6</td>
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<td>2390</td>
<td>4640</td>
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<td>8700</td>
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<td>61</td>
<td>72</td>
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<tr>
<td>13</td>
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<td>8.9</td>
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<td>4531</td>
<td>8591</td>
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<tr>
<td>14</td>
<td>South Asia (West)</td>
<td>22,822</td>
<td>33,862</td>
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<td>2900</td>
<td>3444</td>
<td>9.1</td>
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<tr>
<td>15</td>
<td>South Asia (East)</td>
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<td>21,803.2</td>
<td>3.0</td>
<td>0</td>
<td>1196</td>
<td>1623</td>
<td>3.9</td>
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<td>16</td>
<td>Low Latitudes</td>
<td>2601</td>
<td>2554.7</td>
<td>0.6</td>
<td>0</td>
<td>109</td>
<td>218</td>
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<tr>
<td>17</td>
<td>Southern Andes</td>
<td>15,994</td>
<td>29,361.2</td>
<td>4.5</td>
<td>23.8</td>
<td>4241</td>
<td>6018</td>
<td>13.5</td>
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<td>New Zealand</td>
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<td>0</td>
<td>71</td>
<td>109</td>
<td>0.2</td>
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<tr>
<td>19</td>
<td>Antarctic and Sub-Antarctic</td>
<td>3274</td>
<td>13,226.74</td>
<td>18.2</td>
<td>97.8</td>
<td>27,224</td>
<td>43,772</td>
<td>96.3</td>
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<tr>
<td>IPCC (2013)</td>
<td>Total</td>
<td>168,331</td>
<td>726,258.3</td>
<td>38.5</td>
<td>113,915</td>
<td>191,879</td>
<td>412.0</td>
<td></td>
</tr>
</tbody>
</table>

Quality issues in some regions need to be solved

- Patagonia
- Tien Shan

- 170,000 glaciers worldwide covering 730,000 km²
- Volume of about 170,000 km³ or 41 cm SLE
- Numbers will change through RGI updates
Where is the boundary of the Greenland ice sheet?

Greenland: separating the GIC from the GRIS

Three connectivity levels were assigned:
CL0: no connection, CL1: weak, CL2: strong

Area of local GIC is 50% larger than assumed
Mean glacier area change rates

- Net area loss in all regions investigated
- High variability in each region (different samples)
- Regions 2, 11, and 16 with more negative values

Area changes in Patagonia: 1985-2000-2014
Mass changes

- Predominantly negative values
- Accelerated loss in the past decades
- High interannual variability in most regions (pentads)
- Different methods (field, ICESat, dDEM) mostly in good agreement

Greenland: ICESat, Karakoram: DEM differencing
Elevation changes in High Mountain Asia

Contribution of glaciers to sea level change

(a) updated from Cogley, 2009
updated from Cogley, 2009: incl. GL
Hirabayashi et al., 2013
updated from Leducq et al., 2011
(arithmetic mean): incl. GL
updated from Leducq et al., 2011
(area weighted): incl. GL
Marzeion et al., 2012

(b) updated from Cogley, 2009
updated from Cogley, 2009: incl. GL
Gardner et al., 2013
Hirabayashi et al., 2013
updated from Leducq et al., 2011
(area weighted): incl. GL
Marzeion et al., 2012
Marzeion et al., 2012: incl. GL
Some key findings ...

• The RGI lists about 170,000 glaciers covering an area of 730,000 km² and a volume of 170,000 km³ (41 cm SLE).
• The area of the glaciers on Greenland (CL0 and 1) is about 50% higher (total 90,000 km²) than previously assumed.
• They contribute c. 30 Gt/yr to the total loss of about 220 Gt/yr (2003-08), specific loss is as high as in the Alps (0.7 m/yr).
• All glaciers contribute about 1/3 to the observed SLR.
• The spatial variability of elevation changes in High Mountain Asia is very high (regionalization required).
• Glaciers in the Karakoram with mass gain are often dynamically unstable (surge type).
• Glacier surface flow velocities have decreased globally.
• Glaciers globally will continue to shrink in the future.

Further Information: www.climatechange2013.org